NASA TECHNICAL NOTE

NASA TN D-2159

REDUCTION OF FOLD-OVER ERRORS IN FLUX-GATE MAGNETOMETERS

by John Dimeff, Murray S. Gardner, and Richard S. Murphy

Ames Research Center
Moffett Field, Calif.

REDUCTION OF FOLD-OVER ERRORS IN FLUX-

GATE MAGNETOMETERS

By John Dimeff, Murray S. Gardner,
and Richard S. Murphy

Ames Research Center
Moffett Field, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

REDUCTION OF FOLD-OVER ERRORS IN FLUX-GATE MAGNETOMETERS

By John Dimeff, Murray S. Gardner,
and Richard S. Murphy

Ames Research Center
Moffett Field, Calif.

SUMMARY

Externally impressed magnetic fields fluctuating at harmonics of the gating frequency may cause significant errors in measurements made with flux-gate magnetometers. These errors are demonstrated theoretically and experimentally. A passive method of reducing these errors is described and experimentally shown to provide a 400-to-1 reduction of errors resulting from fields fluctuating at the gating frequency.

INTRODUCTION

Traditionally, knowledge of the composition, structure, and dynamics of the sun has been based on observations of its radiations and fields from earth-bound laboratories. The effects of the earth's environment on these observations are by no means small and are themselves the objects of careful scientific scrutiny. Since many thousands of separate observations have been carefully compared for consistency, the effects of the earth's environment have become reasonably well understood. This situation has been altered by the newly acquired ability to place observational apparatus in remote regions of space: on the one hand, it has been improved since we can now make observations free from the disturbing influences of the earth's environment; on the other hand, it has been degraded because our limited ability to transmit data from remote space vehicles raises questions relative to the adequacy of the observations themselves.

Magnetic field measurements from space probes have been made in a typical manner. Measurements of distant magnetic fields have come primarily from the flights of Pioneer V in the spring of 1960 (ref. 1) and Mariner II in August 1962 (ref. 2). Those from Pioneer were made with a spin-coil magnetometer; those from Mariner, with a triaxial flux gate which measured the magnitude of three components of the field every 37 seconds. It is clear that the extremely limited number of observations prevent the experimental consistency checks so invaluable in detecting experimental errors. Further, both the Pioneer V and Mariner II experiments were constrained by spacecraft requirements for weight, power, and data volume. These constraints have, in turn, suggested (and, indeed, will continue to suggest) the use of lightweight, low-power instruments, such as flux-gate magnetometers. While these

magnetometers offer several attractive advantages, their readings are subject to ambiguity resulting from the frequency components of the unknown dynamic fields being multiplied by the gating fields. This same kind of error can occur in many modulated or sampled-data systems, including spin-coil magnetometers and carrier-current and chopper-modulated amplifiers. It is commonly referred to as "aliasing," "spectral-folding," or "fold-over" error.

Mention of fold-over errors in the literature pertaining to magnetometers has been noted in few instances. This is not surprising since, first, errors resulting from fold-over cannot be differentiated easily from real data, and, second, there is reason to argue in many particular cases that fields in the troublesome frequency regimes may not occur with sufficient intensity to cause significant errors.

It is the purpose of this paper to present a simplified theoretical development of the ambiguities together with a suggested method of reducing the errors. Experimental results are presented to indicate the possible magnitude of the error and the degree of improvement attained with the suggested corrective method. The simplicity of the corrective equipment, its low weight, its lack of power consumption, and its ability to effect a significant reduction of fold-over errors suggest its possible inclusion as a part of equipment used for experiments on unknown fields even where the likelihood of error is thought to be small.

DESCRIPTION OF FOLD-OVER ERRORS

If the magnetic field to be measured has a component along the axis of a magnetic core whose permeability is varied periodically (gated), the flux that results will vary in a manner determined by the permeability variations and the magnitude and frequency of the externally impressed field.

Consider now the voltage, E, developed in a coil solenoidally wound around the magnetic core of the flux-gate magnetometer in response to a varying field, impressed along its axis. Let the effective permeability along the axis be represented by

$$\mu = \mu_a + \mu_1 \cos \omega t + \ldots + \mu_n \cos n\omega t + \ldots$$

where ω is the angular gating frequency, μ_a is the average value of the permeability, and μ_n is the magnitude of the permeability for the nth harmonic of ω. Further, let the externally impressed magnetic field, H, over a sufficiently long time interval, T, be described by a Fourier series,[1]

---

[1]In the most general case, the Fourier series for μ and H would also contain sine terms. These would introduce additional terms in the following product expansion, but would not introduce any new frequencies or change the basic character of the phenomenon. For the present purpose, since the objective is an understanding of the nature and source of the fold-over errors rather than an exhaustive treatment of their magnitudes, it is preferable to deal with the simpler case involving only cosine terms in order that the nature of the results not be obscured by the multiplicity of terms.

$$H = H_a + H_1 \cos \rho t + \ldots + H_m \cos m\rho t + \ldots$$

where H_a is the average value of the field; ρ is the lowest angular frequency component of the Fourier series, $2\pi/T$, and is small compared to the highest information frequency component of the impressed field; and H_m is the peak field intensity of the component occurring at frequency $m\rho$. Then the voltage developed in the coil is given by the relationship

$$E = K \frac{d}{dt}(\mu H) = K \left(\mu \frac{dH}{dt} + H \frac{d\mu}{dt} \right)$$

$$= -K \left[\rho\mu_a \sum_{m=1}^{\infty} H_m m \sin m\rho t + \omega H_a \sum_{n=1}^{\infty} \mu_n n \sin n\omega t \right.$$

$$+ \rho \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} (\mu_n \cos n\omega t)(H_m m \sin m\rho t)$$

$$\left. + \omega \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} (\mu_n n \sin n\omega t)(H_m \cos m\rho t) \right]$$

Each cross-product term may be expressed in terms of the sum and the difference of the two frequencies concerned, giving

$$E = -K \left[\rho\mu_a \sum_{m=1}^{\infty} H_m m \sin m\rho t + \omega H_a \sum_{n=1}^{\infty} \mu_n n \sin n\omega t \right.$$

$$+ \frac{\rho}{2} \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} m\mu_n H_m \sin(m\rho \pm n\omega)t$$

$$\left. - \frac{\omega}{2} \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} n\mu_n H_m \sin(m\rho \pm n\omega)t \right]$$

If a band-pass filter is added to the sensing coil and designed to provide a bandwidth of 2α cps at a center frequency of ω (2α being much smaller than ω), then the only terms passed by the filter will be those having frequencies of $\omega + C\alpha$, where C may have any value between -1 and $+1$. Of the first series those components are passed for which $m\rho = \omega + C\alpha$. These components represent magnetic field fluctuations of frequencies approximating the gating frequency and cause errors since they are indistinguishable from the steady-state and slowly varying components the instrument is intended to measure. The only component of the second series that is passed by the filter is the term for $n = 1$. This is the desired term which measures the d-c component of the field, H_a. It is clear that if $C = 0$, the fold-over term

derived from the first series is indistinguishable from the desired term
derived from the second series, except that the respective coefficients,
$\mu_a H_{(\omega/\rho)}$ and $\mu_1 H_a$, differ. They derive from various frequency components of
the magnetic field and the varying permeability and could be individually
determined if independent measurements were made. Since this essentially
requires a second instrument to provide a measurement of the strength of the
mth harmonic of the impressed field, it is clearly undesirable.

Considering now the third and fourth series in the expression for E,
we see that the only components of the sum and difference frequencies that
will be passed by the filter are those described by the expression

$$m\rho \pm n\omega = \omega + C\alpha$$

For the case where n = 1, those components will be passed for which

$$m\rho = C\alpha$$

or

$$m\rho = 2\omega + C\alpha$$

Components in the first group are in the frequency range of interest. Those
in the second group are clearly outside the frequency range (0 to α) that
represents the dynamic information of interest, and the signals they introduce
will cause fold-over errors. For any $n \neq 1$, it is clear that additional
terms occur which satisfy the conditions of the experiment and introduce
fold-over errors.

To summarize the above: The readings from flux-gated magnetometers may
appear to be the result of steady and/or slowly varying fields when in fact
they are the results of unknown higher frequency components "folded" from the
higher frequency portions of the magnetic spectrum into the pass-band of the
instrument by the process of multiplication during sampling. To identify and
remove these fold-over errors in a typical instrument would require independ-
ent measurements of the various interfering frequency components and
determination of the sensitivity of the instruments to them.

REDUCTION OF ERRORS

Two methods of reducing these ambiguities were considered. The first
involved reducing the high-frequency fields impressed on the flux gate; the
second consisted in sensing the magnitude and phase of the fields and subse-
quently correcting the flux-gate output. Auxiliary sensing equipment would
generally consist of a companion magnetometer that would not be based on a
sampling technique and would be insensitive to stray magnetic field components
created by the gating of the primary magnetometer. Although this second

technique may be feasible, it was decided that because of the increase of power, complexity, and weight, and the loss of reliability, an investigation of the former method would be more productive. Accordingly, an experimental effort was made to evaluate the effectiveness of a passive conducting shield which would completely enclose the flux gate.

Oscillating magnetic fields create eddy currents in a conducting shell which, in turn, generate countermagnetic fields. The incident external fields decrease to $1/e$ of their magnitude in a distance described as the skin depth, δ. If the conductor is several skin depths thick, the penetration of the external field can be reduced effectively. The maximum thickness allowable will be dictated largely by the frequency response required from the magnetometer. To test the effectiveness of the passive shielding technique in reducing fold-over errors, two spherical aluminum shells were constructed with outside diameters of 6.4 to 7.8 cm and with a thickness corresponding to 3δ at the gating frequency, $f = \omega/2\pi = 2 \times 10^4$ cps, as determined by the relationship

$$\delta = (2r/\mu_s\omega)^{1/2}$$

where r is the resistivity and μ_s is the permeability of the shield.

In addition to attenuating the high-frequency components of the externally impressed fields, it is clear that a conducting shield which intercepts lines of flux created by the gating will influence the operation of the flux-gate magnetometer itself. To minimize external fields created by the gating of the magnetometer, an orthogonal gating field arrangement was employed following Cornell University's modification of the Schoenstedt design (ref. 3). The design of the Cornell flux gate is represented schematically in figure 1.

The gating drive coil is wrapped toroidally around a tubular core of 4.5-cm length, 0.4-cm O.D., and 0.2-cm I.D. Current in the drive coil creates a circular magnetic field inside the core. The secondary coil is solenoidally wound so as to detect any change in flux along the axis of the core. A cyclic current (fig. 2) is impressed in the drive coil with an amplitude great enough to saturate the core in the toroidal direction. The resulting periodic variation in μ_x is shown in figure 3.

For testing the sensitivity of the various magnetometer shield configurations, the assemblies were placed inside a Helmholtz coil used to generate the incident fields.

The normalized flux-gate outputs, shielded and unshielded, are shown in figure 4 as a function of frequency of the externally impressed field. The lower abscissa on figure 4 indicates the apparent frequency of the field being measured, that is, the frequency of the signal derived from the flux gate after detection and filtering.

The effective sensitivity of the unshielded flux-gate magnetometer for varying external fields whose frequencies nearly equal the gating frequency is approximately ten times as great as its sensitivity to low-frequency

fields. Lesser peaks of response were experimentally observed when the frequency of the impressed magnetic field was equal to a harmonic of the gating frequency. The previous analysis indicates that the high sensitivity to field components near the modulation frequency is due to the large value of the d-c, or average value, coefficient in the Fourier series describing the gating process. The spurious peak would be attenuated if the μ_x variations were modified as shown in figure 5 so as to reduce the average-value component. With the cores used, however, this would necessitate a larger power input to the probe, which is not desirable. Alternatively, the use of magnetometer cores with square loop characteristics (such that the permeability, μ_x, after release of the saturating magnetomotive force is essentially that of air) would provide the more desirable time variations of μ_x shown in figure 5 without requiring high driving power.

In addition to the unshielded response, figure 4 also shows the flux-gate response with a double and a single shield surrounding the probe. The reduction of the fold-over error for the double shield is approximately 400:1 and for the single shield approximately 47:1. Although no data were obtained for higher frequencies, it seems obvious that the shielding should be more effective for the harmonics of the gating frequency than for the fundamental.

All points on the response curves are normalized to the response of the flux gate to a 100 cps external field without a shield. The reductions in sensitivities obtained at 100 cps for the various shield configurations give an indication of sensitivity degradation due to coupling between the gating flux and the shields. It may be seen that a thicker shield or smaller radius causes a greater reduction of gain in the information band.

While no attempt has been made to optimize the geometries of the eddy current shields, it has been clearly demonstrated that flux-gate system response to magnetic fields fluctuating at frequencies near the critical gating frequency can be significantly reduced. Reduction of fold-over ambiguities, therefore, has been accomplished by means of a lightweight passive device so simple and reliable that it warrants consideration in the design of any gated magnetometer probe designed for use in uncertain environments.

Ames Research Center
    National Aeronautics and Space Administration
        Moffett Field, Calif., July 29, 1964

REFERENCES

1. Cahill, L. J., Jr.: Magnetic Field Measurements in Space. Space Sci. Rev., vol. 1, 1962-63, pp. 399-414.

2. Coleman, P. J., Jr., Davis, Leverett, Jr., Smith, E. J., and Sonett, C. P.: Interplanetary Magnetic Fields. Science, vol. 138, no. 3545, Dec. 7, 1962, pp. 1099-1100.

3. Ling, S. C.: A Flux-Gate Magnetometer for Space Application. AIAA paper 63-187, 1963.
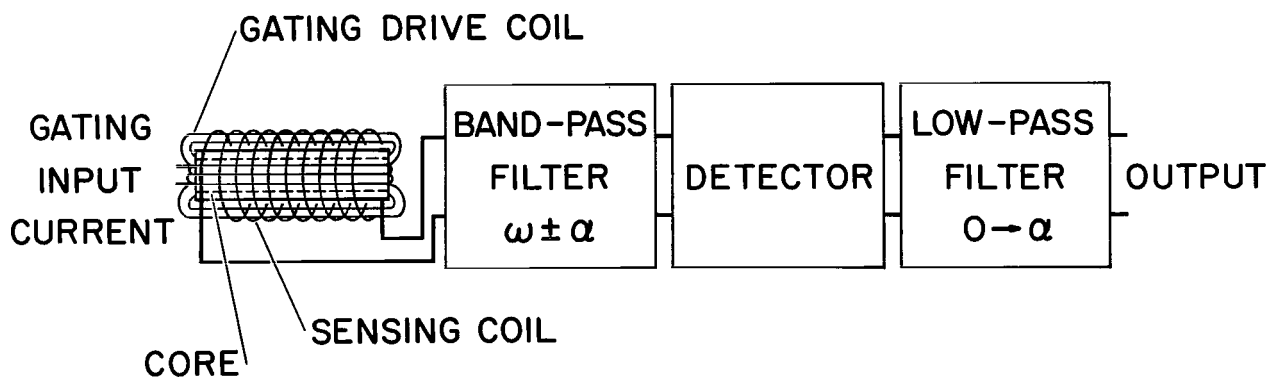
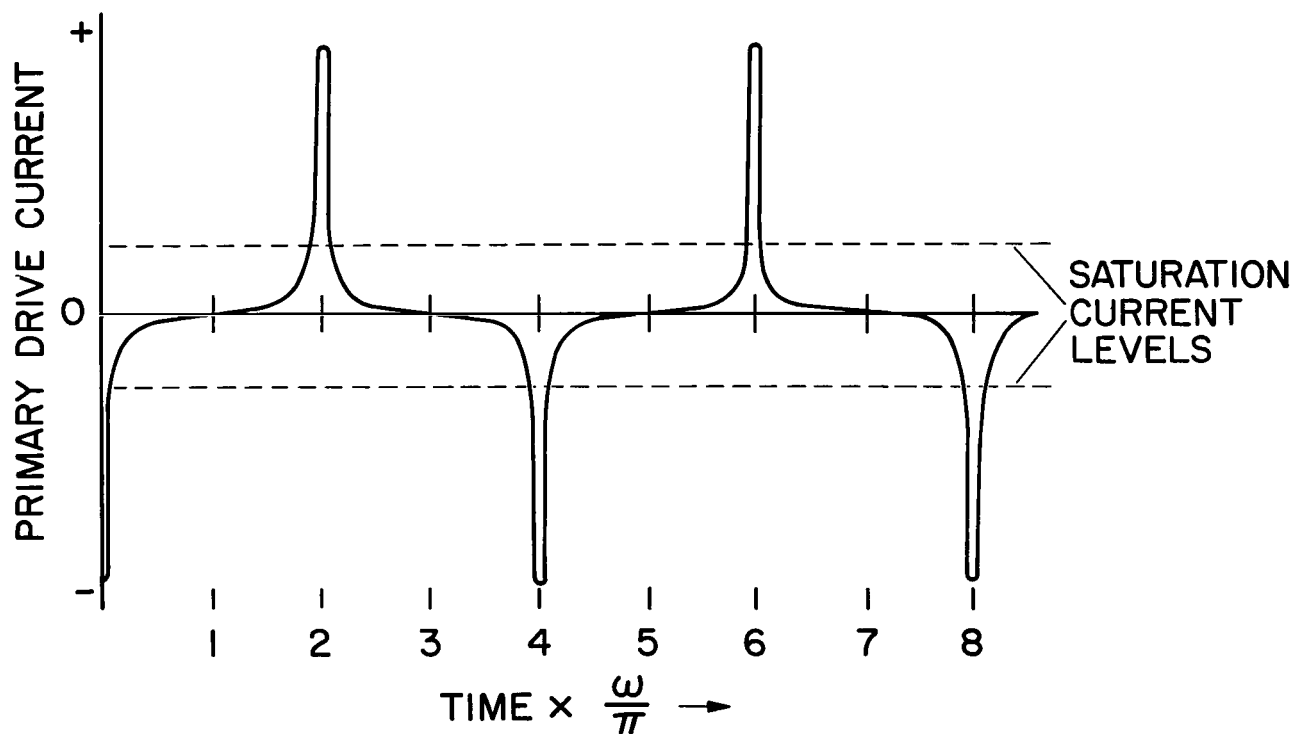Figure 1.- Schematic representation of the flux-gate magnetometer.

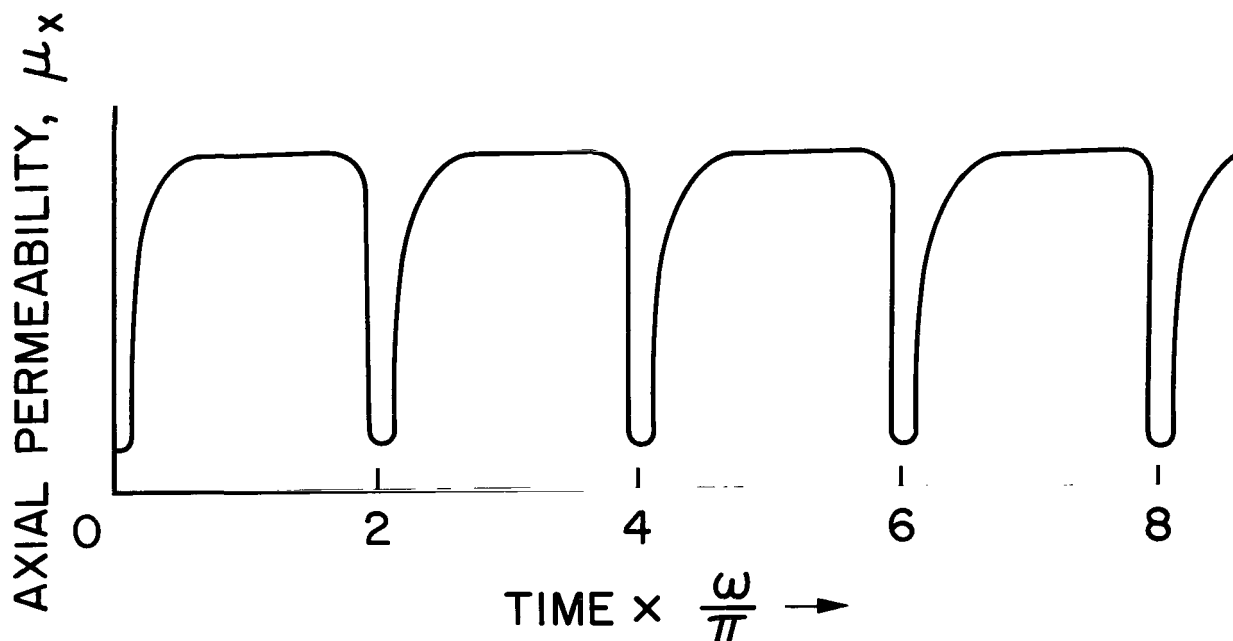Figure 2.- Flux-gate drive current vs. time.

AXIAL PERMEABILITY, μ_x

TIME $\times \dfrac{\omega}{\pi} \longrightarrow$

Figure 3.- Effective axial permeability as a function of time.

f_h ACTUAL FREQUENCY OF THE EXTERNAL FIELD, cps

f_0 APPARENT FREQUENCY OF THE EXTERNAL FIELD
AFTER DETECTION, cps

—————— UNSHIELDED FLUX-GATE RESPONSE

— — SINGLY SHIELDED FLUX-GATE RESPONSE

- - - - DOUBLY SHIELDED FLUX-GATE RESPONSE

NORMALIZED FLUX-GATE RESPONSE

10^2 10^1 10 10^{-1} 10^{-2} 10^{-3}

FIELD FREQUENCY
EQUAL TO GATING
FREQUENCY, ω

10^2 $5 \cdot 10^2$ 10^3 $5 \cdot 10^3$ 10^4 10^5 f_h

10^2 $2 \cdot 10^2$ $5 \cdot 10^2$ 10^3 500   0   500 f_0

Figure 4.- Frequency response of the flux-gate magnetometer.

10

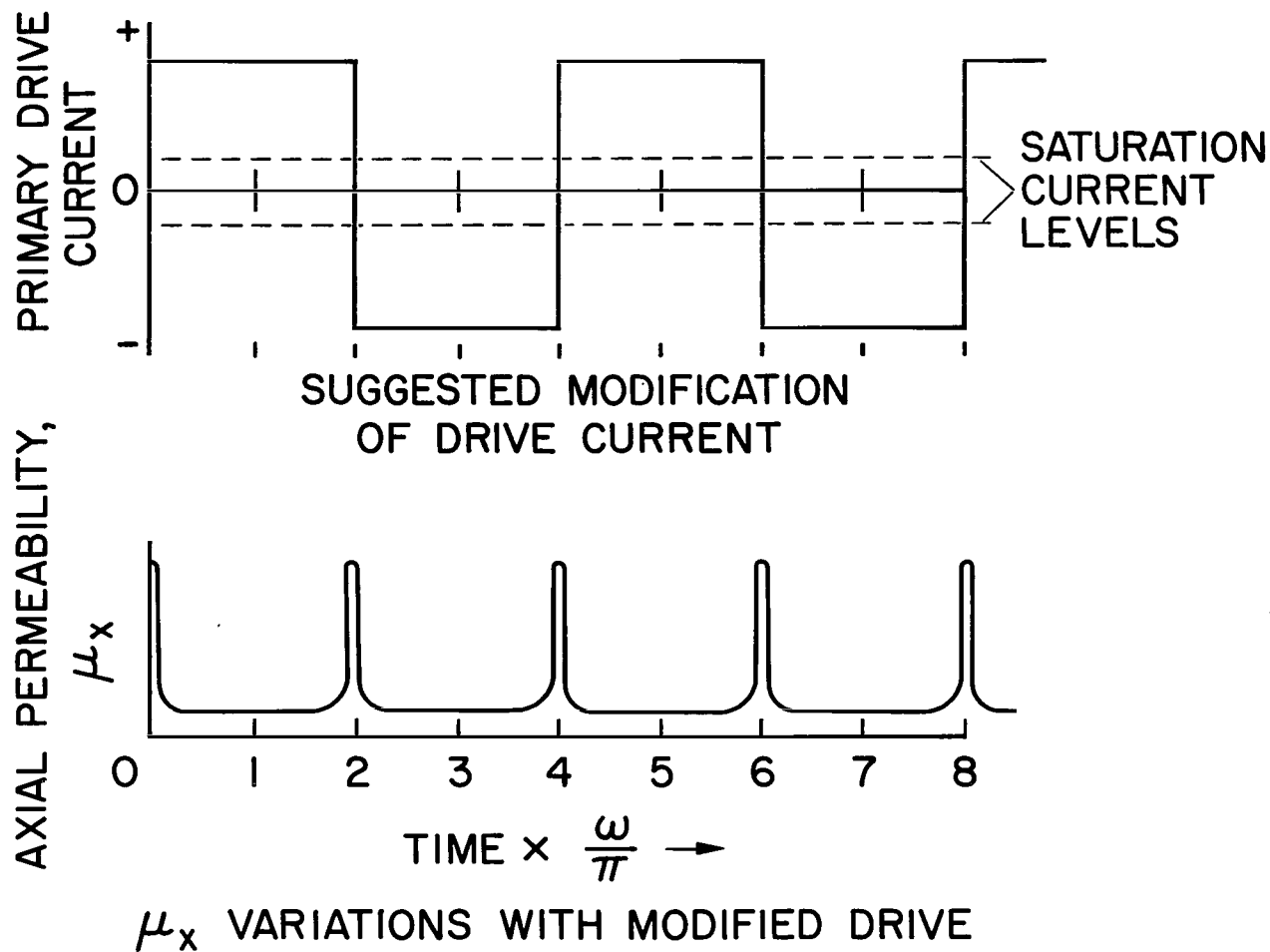SUGGESTED MODIFICATION
OF DRIVE CURRENT

μ_x VARIATIONS WITH MODIFIED DRIVE

Figure 5.- Modified gating for reduction of fold-over effects.